Disks surrounding Cataclysmic Binaries

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Abstract. Observations of Cataclysmic Variables show a number of phenomena that do not fit easily into the standard magnetic braking scenario. These include the large spread in mass transfer rates, the low surface temperatures of many of the companion stars, and evidence for material at low velocities. We propose that these anomalies have a common cause: the presence of a circumbinary (CB) disk. This may be a significant component of mass transferring binaries in general. Direct detection of such CB disks may be possible but difficult, because of their low luminosity and spectral energy distribution peaking in the mid-IR.

1. Introduction

The standard picture for the evolution of Cataclysmic Variables (CV), now nearly 2 decades old, has been reasonably successful as a framework for interpreting the phenomenology of CV. In this interpretation, angular momentum loss by gravitational waves and magnetic braking causes cataclysmic binaries to evolve from longer to shorter orbital periods (P), with magnetic braking dominating above the 'period gap' ($P > 3$ hr), and a lower braking rate below this gap ($P < 2$ hr). This picture explains some overall statistical properties, for example the existence of the period gap itself and the higher mass transfer rate above the gap compared to short period systems.

An additional element of the phenomenology, independent of the magnetic braking scenario but not in conflict with it either, is the existence of outflows from the accretion disk. Evidence for outflows comes from the profiles in UV-lines seen in outbursts of Dwarf Novae (e.g. Woods et al. 1992), possibly the single-peaked line profiles of the novalike (NL) and SW Sex binaries (see however Hellier 2000 for an alternative explantation of these line profiles), and other indications for outflow (e.g. Long et al. 1994).

2. Anomalies

A number of observations, however, are hard to fit into the standard picture:

- 1 A major problem is the very large spread in inferred mas transfer rates at a given orbital period (Patterson 1984; Warner 1987). The braking scenario predicts a close relation between mass transfer rate and orbital period.

- 2 An extreme form of the spread in mass transfer rate is shown by the short-period super soft sources (SSS). Though some SSS have long orbital periods and their large transfer rates can be explained as the result of expansion of the secondary by nuclear evolution, several have short orbital periods, in the same range as the novalike systems. The secondaries at such periods are too small to have significantly evolved. An unknown process causes these binaries to transfer mass at rates sufficient ($\sim 3\,10^{-7}\mathrm{M_\odot yr^{-1}}$) to sustain the observed steady burning of Hydrogen at the surface of the White Dwarf primary star.

- 3 A second unexpected fact is the distribution of the novalike systems, which cluster at periods (around 4-6 hr) just above the period gap, whereas the braking scenario predicts them to predominate at longer periods, where the predicted mass transfer rate are highest.

- 4 The single peaked profiles of the emission lines in the SSS, the SW Sex stars, the AM CVn stars and many NL systems show that in some cases the emission lines are not predominantly formed in the accretion disk, but in optically thin material of large emission measure somewhere else in the system. The phenomenon is particularly striking in some AM CVn systems, (cf. Warner 1995), where a narrow emission line is seen on top of a broad double peaked emission line from the accretion disk. This phenomenon has been interpreted in terms of circumbinary material already by Solheim and Sion (1994). A similar phenomenon may be the low-velocity emission peaks in supersoft sources like QR And (Deufel et al. 1999).

- 5 'Additional light' in systems with parameters such that mid-eclipse of the primary star and accretion disk should be total. In some of these systems the light remaining at mid-eclipse can not be explained by the spectral type of the secondary star. In the case of UU Aqr the spectrum of the additional light has been determined; it shows the characteristics of optically thin emission (Baptista et al. 1998).

- 6 Comparison of the spectral types of the secondary stars with theoretical models (Baraffe and Kolb 2000) shows them to be significantly cooler, on average, than main sequence stars, as if they were less massive and over-expanded as a result of a recent prolonged period of large mass transfer.

- 7 Superhumps above the period gap. The so-called superhumps, a feature in the lightcurve that drifts in orbital phase, is thought to be due to a resonance in the accretion disk. This resonance can only occur at low mass ratios, such as occur in the short-period systems. They are also seen in several novalike systems, however (Patterson, 1999). This would be another indication that the mass of the secondary in such systems above

the period gap is often smaller than expected from the standard braking scenario.

- 8 Pile up at the minimum period. The standard braking scenario predicts that the orbital evolution of CVs slows down as they approach the minimum orbital period, after which their orbital period increases again at a very slow rate. Most old CVs are predicted to end up somewhere near this minimum period. The observed period distribution does not show such a spike in the distribution (cf. Kolb & Baraffe 1999). Though the observations are probably biased against detection of these systems because of their low quiescent luminosity and the long recurrence time of their outbursts, the discrepancy is large, and can probably not be explained entirely by these selection effects (Kolb 2001; Marsh et al. 2001; and references therein; Gänsicke et al. 2001).

- 9 Value of the minimum period. The theoretically predicted value of the minimum orbital period of CVs (excepting thiose with helium star companions) is around P=70 min, the observed value around 80 min. Stellar models are believed to be sufficiently accurate, but agreement with observations would be obtained if the mean mass transfer rate of the short-period systems were at least a factor 3 higher than assumed in the standard braking scenario.

- 10 The rate of magnetic braking. The standard formulas used for angular momentum loss by magnetic stellar winds is somewhat of an extrapolation, based on loss rates inferred from stars rotating much more slowly than the secondaries of CVs. Recent work by Andronov, Pinsonneault and Sills (2001) indicates that this extrapolation overestimates the angular momentum loss rate in CVs by as much as 2 orders of magnitude. If this is correct, the observed mass transfer rates in CVs can not be due to magnetic braking.

3. Interpretation

Though some of the anomalies listed are possibly red herrings which may find unrelated explanations, they all fit qualitatively into the suggestion made here, a CB disk, i.e. a disk surrounding the binary. If these exist, they would be a major, thus far unrecognized component of Cataclysmic binary systems.

A CB disk would be an additional source of angular momentum loss for the binary. The tides raised in the CB disk by the orbiting binary transfers angular momentum to it, and prevent it from spreading inward. Depending on the surface density of the CB disk, the angular momentum loss from the binary would differ, and with it the mass transfer rate. The SSS would, in this interpretation, be the relatives (Greiner et al. 2000) of NL and SW Sex systems, the difference being the presence of a more massive CB disk.

The increased mass transfer rates caused by CB disks would be systematic, since a CB disk would dissipate only very slowly by spreading. This might explain the apparent overexpansion of the secondary stars. A higher mass trans-
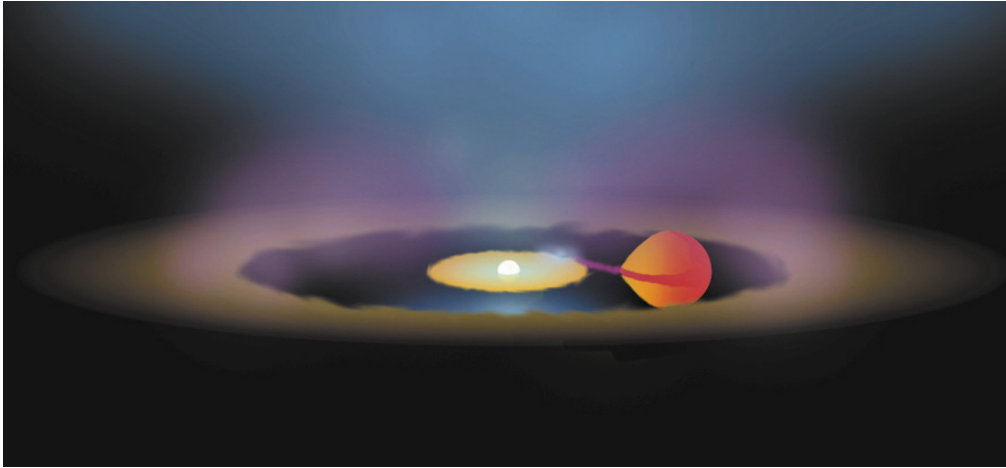
Figure 1.   Artist's impression of a circumbinary disk around a cata-
clysmic binary. The haze above the disk indicates the outflow from the
accretion disk. A slow component of the outflow condenses onto the
CB disk and feeds it.

fer rate would also help to explain the discrepancy between the observed and
predicted values of the period minimum.

The obvious question is how a CB disk would be formed. One possibility
would be that it is a 'fossil': a remnant from a late stage of the common envelope
(CE) evolution phase in which the cataclysmic binary was formed (for a review
see Taam & Sandquist 2000). This could happen as a 'fall back' process at
the time the common envelope becomes optically thin. Given the difficulty of
computing the CE evolution, it is hard to estimate the likelihood of such a
formation channel for CB disks.

A second possibility is that CB disks form as a by-product of mass loss
from the system. The single peaked line profiles in SW Sex stars indicate outflow
velocities up to 2000 km/s, which is well above the escape speed from the binary.
There is large optical depth in these lines at lower velocities as well, however,
so that a significant outflow component at velocities of the order of the escape
speed from the binary (a few 100 km/s) or lower may also exist. This would
be material that would 'hang around' the binary rather than being ejected. It
would naturally form a CB disk by cooling and settling to the equatorial plane.
It is hard to quantify from the observations how much material might condense
into a CB disk in this way. Instead, we have used model calculations in which
this uncertainty is parametrized. These show that a relatively minor amount
would suffice to build up substantial CB disk.

4.   Model calculations

For the model calculations (Spruit and Taam 2001, Taam and Spruit 2001,
Dubus et al. 2001) we have made use of the observation that evidence for
outflows is strongest in systems with high mass transfer rates: dwarf novae in

outburst, the SW Sex stars, supersoft sources and the AM CVn stars. This suggests that mass loss by outflows increases with mass transfer rate. We have made the simple assumption that the two are proportional. In addition, we have assumed that of the outflow, a fixed fraction settles into a CB disk. The mass input rate $\dot{M}_{\mathrm{CB}}$ into the CB disk is thus a given fraction δ of the mass transfer rate $\dot{M}$.

4.1. Feedback

The consequence of the assumed proportionality between mass input into the CB disk and the mass transfer rate is a positive feedback: once a CB disk is present, the angular momentum it extracts from the binary enhances the mass transfer rate from the secondary to the primary. This increases the mass input rate into the CB disk, increasing its surface density. With this higher density the increasing torque on the binary in turn increases the mass transfer rate. Though the mass transfer might initially be caused by the standard magnetic braking process alone, the mass building up in the CB disk would eventually make this feedback strong enough to become unstable. From this point on, the mass transfer rate and the input rate into the CB disk would increase in step exponentially. In this way the large mass transfer rates in for example the short-period supersoft sources could develop. In our interpretation, these would be descendants of novalike systems, as suggested before by Greiner et al. (2000).

We call the phase of high mass transfer resulting from this instability 'accelerated mass transfer' induced by the CB disk. The calculations show that the orbital period typically 'bounces' shortly after accelerated mass transfer sets in (if the secondary is not significantly evolved) . The more rapid mass loss from the secondary causes it to expand, forcing the orbital period to increase. This contrasts with the evolution under standard braking, which results in an essentially monotonically decreasing orbital period.

Whether the effect of a CB disk on the binary becomes significant depends mostly on the mass input rate into it. Analytic results based on the above assumptions (Spruit and Taam 2001) suggested that a minimum value of δ around 10^{-3} would be sufficient to cause accelerated mass transfer to occur. The precise value is unfortunately somewhat sensitive to the physics determining the viscous spreading of the disk. Remarkably, the uncertain value of the viscosity itself, as parametrized through a constant α-viscosity, has only a weak influence. This is because the torque exerted by the disk is proportional to $\alpha\Sigma_{\mathrm{i}}$, where Σ_{i} is the surface density at the inner edge of the disk. A larger value of α is compensated largely by the more rapid spreading of the disk, which lowers Σ_{i}. More important than α itself is the relative variation of the viscosity through the disk. Calculations using more detailed physics for the CB disk (Taam and Spruit 2001) indicated that a rather high value of δ, around 10^{-2}, would be needed for accelerated mass transfer, but these did not include the effect of convection on the structure of more massive CB disks. This was included by Dubus et al. (2001), together with a more sophisticated method for calculating the viscous evolution of the CB disk. In these so far most realistic calculations values of δ around 10^{-4} were found to be sufficient to cause a rapid acceleration to high transfer rates to happen within a Hubble time.

5. Consequences of the presence of CB disks

5.1. Dissolution of the secondary

In the standard magnetic plus gravitational radiation braking scenario, the mass transfer rate declines rapidly with decreasing secondary mass, such that complete transfer of the secondary mass does not happen within a Hubble time. With torques due to a CB disk the evolution of the secondary is more interesting. In the 'accelerated' transfer phase, the angular momentum loss is determined by the surface density of the CB disk, rather than by the secondary star. Hence the mass transfer rate stays finite as the secondary mass vanishes. As a consequence, the secondary dissolves completely within a finite, relatively short time once a phase of accelerated mass transfer has set in, and leaves a single white dwarf.

This would have significant effects on the distribution of systems with orbital period. If a substantial fraction of all systems go through a CB-induced phase of accelerated mass transfer, they would disappear from the CV population, and the pile-up of systems towards the period minimum around 80 min. would be replaced by a gradual decline of the number of systems. This would be more in line with current observations (cf Kolb 2001).

5.2. White dwarfs with planets?

After dissolution of the companion, the white dwarf primary would be left as a 'white widow', with a CB disk still surrounding it. The mass in this disk could be substantial, perhaps as much as $10^{-3} - 10^{-2} \, \mathrm{M_\odot}$. As this disk cools, it may well form planets in the same way as a protoplanetary disk. It remains to be seen whether such planets would be detectable, for example through Doppler shifts of the NLTE cores of the Balmer lines of the WD.

5.3. The period gap

The CB interpretation given here implies a large systematic spread in mass transfer rates. [As opposed to cyclic mass transfer variations such as proposed by King et al. (1995). In this mechanism the average mass transfer rate does not spread much]. Though this spread explains a number of facts such as the observed varying degree of overexpansion of the secondaries, it is not easily compatible with the explanation of the period gap in terms of disrupted magnetic braking. The period gap gets 'washed out' if the long-term transfer rate differs too much between systems. It remains to be seen whether a plausible alternative explanation of the gap can be found within the CB scenario.

6. Observability

One may wonder how it is possible that something as serious as circumbinary disks around CVs could have escaped detection so far. On closer inspection, however, it turns out that such disks would in fact be rather difficult to observe. On the one hand, the luminosity of a CB disk is low. Though it extracts a lot of angular momentum, this happens at a large distance in a shallow gravitational potential, and is thus accompanied by little energy dissipation. This makes them inconspicuous against the very bright accretion disk, which processes material

deep in the potential well of the primary. Secondly, the size of the CB disk is such that its spectral energy distribution peaks in the poorly accessible mid IR (at 3-10μm, cf. the models of Dubus et al., 2001). Finally, model calculations show that the CB disk probably lies in the shadow of the outer part of the accretion disk. Enhanced brightness through illumination of the disk by the bright central regions of the accretion disk is thus also unlikely.

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